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International Space Station observations offer an opportunity to understand plant function

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Author Contributions
ENS is the lead writer for the manuscript, DS lead discussions and helped articulate the key points of discussion for the manuscript, RP provided HISUI and OCO3 information and sub-figures associated with Figure 2 as well as with edits for the manuscript, SS helped edit the general text, developed Figure 2 and provided text for terrestrial biosphere models section, AS helped edit the general text and provided text for terrestrial biosphere models sections, LD provided the GEDI sub-figure in Figure 2 and text describing GEDI, JBF helped with general editing and provided the ECOSTRESS sub-figure in Figure 2, FF helped with general editing, SU helped develop the original manuscript outline, RD, AS and PW were key in contributing ideas for the manuscript.

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Summary

Technologies that will make novel observations of ecosystem composition, structure and function are planned for deployment on the International Space Station in 2018, providing ~1 year of synchronous observations. Here, the suite of instruments are discussed and how such observations can be used to constrain global models and improve our understanding, forecasting, and benchmarking of the current state of terrestrial ecosystems.

1. Introduction

Space-based observations are increasingly central to global ecology, opening windows to address questions pertaining to the carbon cycle, biodiversity, productivity and disturbance. Until recently, satellite observations provided a limited range of observations, albeit critical ones, relating light absorption to support plant growth, disturbance and land use/land cover change. These observations have revolutionized our knowledge of global ecology, but have not addressed a series of critical questions of ecosystem process that must be resolved in order to reduce uncertainty in future climate and ecosystem service projections. These key questions have been addressed in local studies, but the findings of these local experiments cannot be tested across broad landscapes with observations from existing satellite technologies. For example, Normalized Difference Vegetation Index (a metric of vegetation greenness often used as a proxy for ecosystem productivity or carbon storage) influences estimates of absorbed photosynthetic active radiation (fPAR) and Leaf Area Index (a metric of one-side leaf area per ground surface area)[1]. Thus, more direct observations of functioning and structure are needed to enable distinct testing and improvement of modeled representations of ecosystem processes.

Questions include:

- How sensitive are ecosystems to temperature and water availability and how will this affect future carbon and energy balances?
- Do diverse plant communities respond to climate change differently from simpler communities?
- Does diversity lead to ecosystems responding non-linearly to change, in ways we cannot predict now?
- How does land management interact with climate to control future disturbance regimes?

Common to all these questions is that they require multiple observations to test specific hypotheses, and reject incorrect model formulations. Fortunately, there are many exciting new developments in remote sensing that will provide key observations of the land (e.g., Sentinel series, BIOMASS, NISAR, etc.).

Although new technology make many key observations feasible, observing platforms with multiple instruments collecting a variety of parameters at synergetic spatial resolutions and coordinated temporal acquisition, particularly at scales needed for management, are uncommon. Yet this is exactly what is needed to resolve how plant function affects ecosystem processes at landscape scales in different regions across the globe. Fortunately, with a coordinated strategy, such an opportunity will arise for ecologists in the next few years!

2. Novel Earth Observations

The International Space Station (ISS) will host four instruments from JAXA and NASA (Table 1) in 2018 that will advance our ability to monitor and model terrestrial ecosystems between latitudes ~50^{o} North and South. Three of the instruments are from NASA and include: the Global Ecosystem Dynamics Investigation (GEDI), the ECOsystem Spaceborne Thermal Radiometer Experiment on Space Station (ECOSTRESS), and the Orbiting Carbon Observatory 3 (OCO-3). All three are being developed for deployment to the ISS in 2018 and will distribute the free data products listed in Table 2. The fourth instrument for deployment also in 2018 is from JAXA and is the Hysperspectral Imager SUIte (HISUI)[1,2]. In complement to HISUI is the German Aerospace Agency (DLR) EnMAP[3], for which the observational plan has already been established, thus it is not the focus of the imaging spectroscopy discussion henceforth. These four instruments will make observations of three-dimensional structure (GEDI) that can be used to scale biochemical signals[4–6] to the canopy level (HISUI) and derive estimates of ecosystem composition, productivity (SIF from OCO-3), and water-use efficiency (a product of ECOSTRESS) at landscape scales. This instrument suite offers a unique opportunity because the drifting ISS platform and pointing capabilities of some of the instruments enable co-location of high-spatial resolution measurements in space and acquisition times covering the diurnal cycle throughout the year (i.e., >20 observations per hour of the day throughout the year).

3. A Call for Coincident Observations

Coordinating the spatial and temporal coincidence of measurements from GEDI, ECOSTRESS, OCO-3 and HISUI would be an opportunity to address ecosystem dynamics that cannot be answered from any one instrument and that have the ability to substantially enhance our understanding of ecosystem responseses to global change. For example, an estimation of carbon sink potential (Figure 1) can be estimated using observations of carbon flux (OCO-3) and carbon storage (LIDAR-derived biomass from GEDI), both of which can be affected by the efficiency of individual plant species (HISUI) to sequester carbon under variable access to water (ECOSTRESS).

Despite added information value from synergistic observations, the protocols and measurement strategies for any one of these instruments do not currently consider the other instruments. Thus, there is an argument and need for collaboration during mission development to coordinate observation strategies and maximize scientific returns on investment. Coordinated observations can include both before and after launch by using aircraft versions of theses spaceborne instruments (e.g., LiDAR for GEDI, PhyTIR for ECOSTRESS, CFIS for OCO-3 and AVIRIS for HISUI). Airborne campaigns with instruments analogous to those deployed for space are frequently used for calibration and validation activities of delivered data products both leading up to and after launch. Furthermore, these instruments may help to scale understanding of ecological processes between ground-based and spaceborne observations. Additional consideration of airborne and ISS observations at the high spatial resolutions and with unique temporal acquisition in the context of other spaceborne observations (e.g., Sentinnel series, Landsat, etc.) can provide additional information for scaling understanding of ecosystem process and function. Thus, efforts to coordinate synergistic observations between the ISS instruments should also consider the utility of and coordinated efforts needed for airborne campaigns and how their observations link with existing and upcoming satellites.

Organizing synchronous observations in space and time at varying scales of resolution will be most useful if future research uses these data by ingesting them into existing information system infrastructure (i.e., models) in order to contextualize the information gleaned from the relatively short period of overlapping observations (~1 year). Specifically, future research can use the ISS observations to establish a baseline for monitoring that can be used to attribute and improve predictions of terrestrial ecosystem changes through time. To do so will require systematic evaluation of processes and ecosystem dynamics, which can be done using models[7]. Terrestrial biosphere model (TBMs) are the primary tool for quantifying the impacts of climate variability, disturbance, and global change on terrestrial ecosystems[8,9]. These models incorporate semi-empirical and mechanistic descriptions of the physiological and biophysical processes and properties of terrestrial ecosystems that drive land-atmosphere fluxes and storage of C, water, and energy across space and time. In addition, TBMs provide the mechanistic framework necessary for integrating various types of data since they can represent ecological processes and functional responses at multiple spatial and temporal scales in a way that leverages our best understanding[10]. In order to improve TBM parameterizations[11], benchmark model forecasts[12], improve process representations, and evaluate alternative model structures, models may need to be adjusted to integrate the ISS observations at the relevant spatial and temporal scales for the processes and functional responses of interest (Figure 2).

Although these flight projects can work together to coordinate observations strategies, there are many logistical issues (e.g., explicit priority of observation areas) for coordinating observational strategies that remain undetermined. Specifically, which areas are of highest priority to image given downlink constraints of instruments on the ISS? And, who is responsible for organizing this across missions? Each instrument system and team is limited and constrained by their budgets and the mandate to deliver on their individual mission requirements first. Thus, it will be necessary for additional efforts by the community in order to seize this opportunity and take full advantage of this spectacular convergence of technical advances that offer a means for constraining our mechanistic understanding of ecological systems across scales suitable for management and regional analyses. Importantly, although each instrument is largely developed and provides significant value independently, in aggregate, the contemporaneous observations from all four instruments could provide observations to support major advances for understanding the carbon and water cycles, and how ecosystem structure, function and diversity interact with them.

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Table 1*. The instruments for deployment on the International Space Station (ISS) are: Global Ecosystem Dynamics Investigation Lidar (GEDI), ECOsystem Spaceborne Thermal Radiometer Experiment on Space Station (ECOSTRESS), the Orbiting Carbon Observatory 3 (OCO- 3), and the Hysperspectral Imager SUIte (HISUI). Each instrument is being designed independently, but the nature of the observations offer an unprecedented opportunity to resolve regional and global scale understanding of ecosystem process and function.*

	DESCRIPTION
GEDI	GEDI is a geodetic-class LIDAR that will measure canopy heights and foliar vertical profiles to establish a baseline of vegetation structure and global terrestrial biomass. GEDI observations leverage a sampling scheme that is then interpolated to produce a map. The sample scheme uses 3 lasers (at 242 pulses/second) to produce observations in 25-m footprints along 10 parallel tracks separated by ~600 m each. Each footprint is separated by 25 m along track.
ECOSTRESS	Because transpiration performs the same cooling function as sweat, when plants close stomata their leaf temperatures increase. This rise in temperature can be detected and such observations at different hours throughout the day are crucial for mapping vegetation water use efficiency as vegetation can close stomata in the afternoon to avoid transpiration exceeding water uptake from the soil, which would result in vegetation stress.
OCO-3	OCO-3 is a pointing instrument that will use three high spectral resolution grating spectrometers to measure solar induced fluorescence (SIF), a measure of photon emission during photosynthetic partitioning that provides a direct proxy for gross primary productivity (GPP) 14, and atmospheric column CO_2, with high precision (± 1 ppm).
HISUI	The HISUI will provide contiguous visible to shortwave infrared (400-2500 nm) surface reflectance at very high spectral resolution (400-979 nm at ~10 nm average/band for 57 bands and 900-2500 nm at ~12.5 average/band for 128 bands).

Table 2. *A list of high-level data products that will provided by each instrument expected for deployment to the International Space Station (ISS) starting in 2017. The instruments are ECOsystem Spaceborne Thermal Radiometer Experiment on Space Station (ECOSTRESS), Global Ecosystem Dynamics Investigation Lidar (GEDI), the Orbiting Carbon Observatory 3 (OCO- 3), and the Hysperspectral Imager SUIte (HISUI). Note: All NASA data products will be freely available for download.*

Data Product Level	ECOSTRESS: 40-60 m pixels, 20-30 samples per hour of the day collected throughout the year	OCO-3: 5 km2 footprint, capable of mapping up to 100 100x100km areas per day	GEDI: ~500 m^2 footprint spaced 60 m along a track with no temporal repeat	HISUI: 30 m pixels with 20 km swath and 10 nm spectral resolution over 0.4-2.5 µm spectral range
2	Surface temperature Emissivity	Atmospheric column CO2 Solar Induced Fluorescence	Height metrics Canopy metrics	Atmospherically corrected surface reflectance with quality assurance (not validated)
3	Evapotranspiration	Gridded Level 2	Gridded level 2	
4	Water Use Efficiency Evaporative Stress Index		Aboveground biomass (footprint and gridded)	

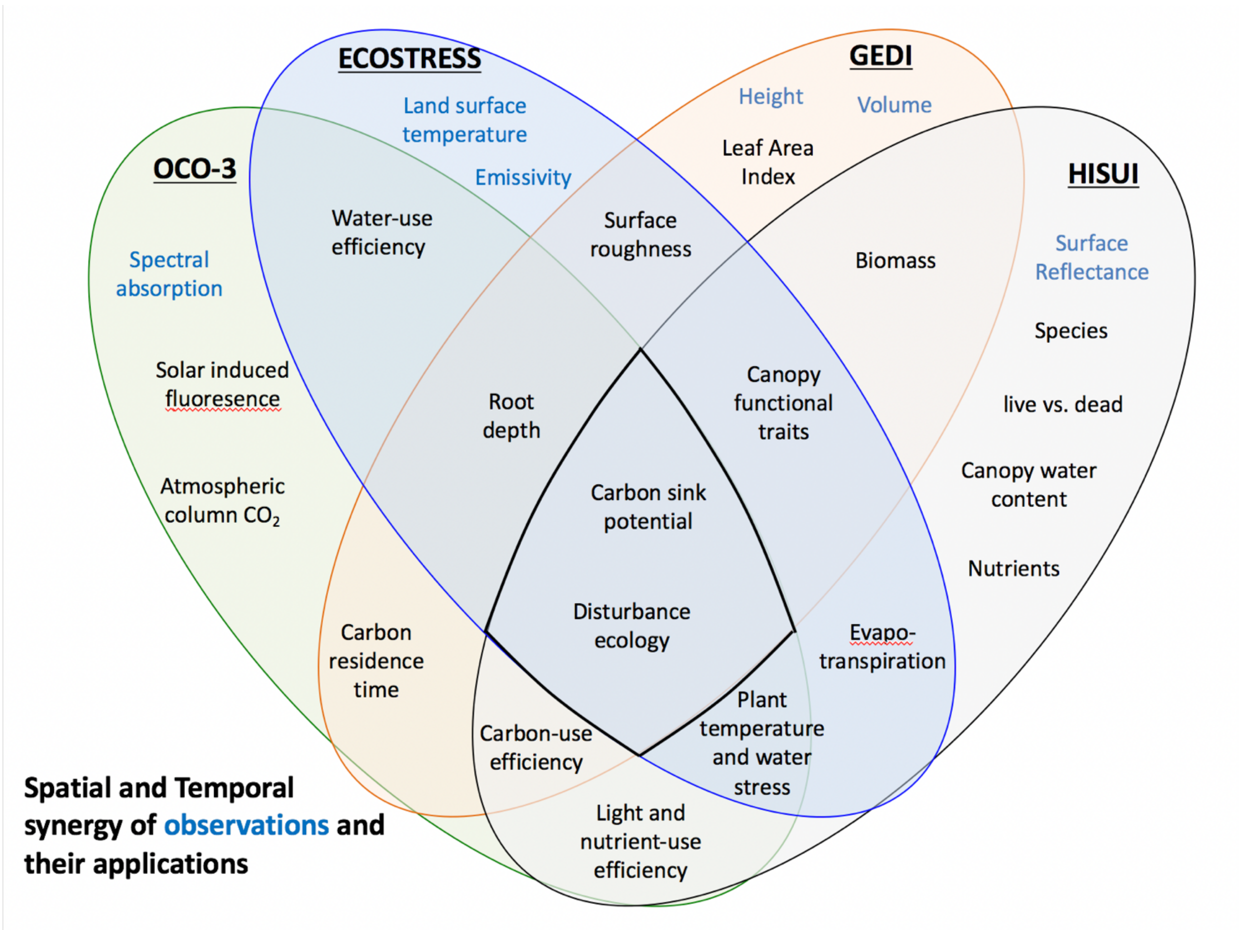

Figure 1. *A pretzel diagram of observations (blue) from each instrument and the synergistic physical parameters that can be derived (black) when observations are taken at synchronous and complementary spatial and temporal resolutions.*

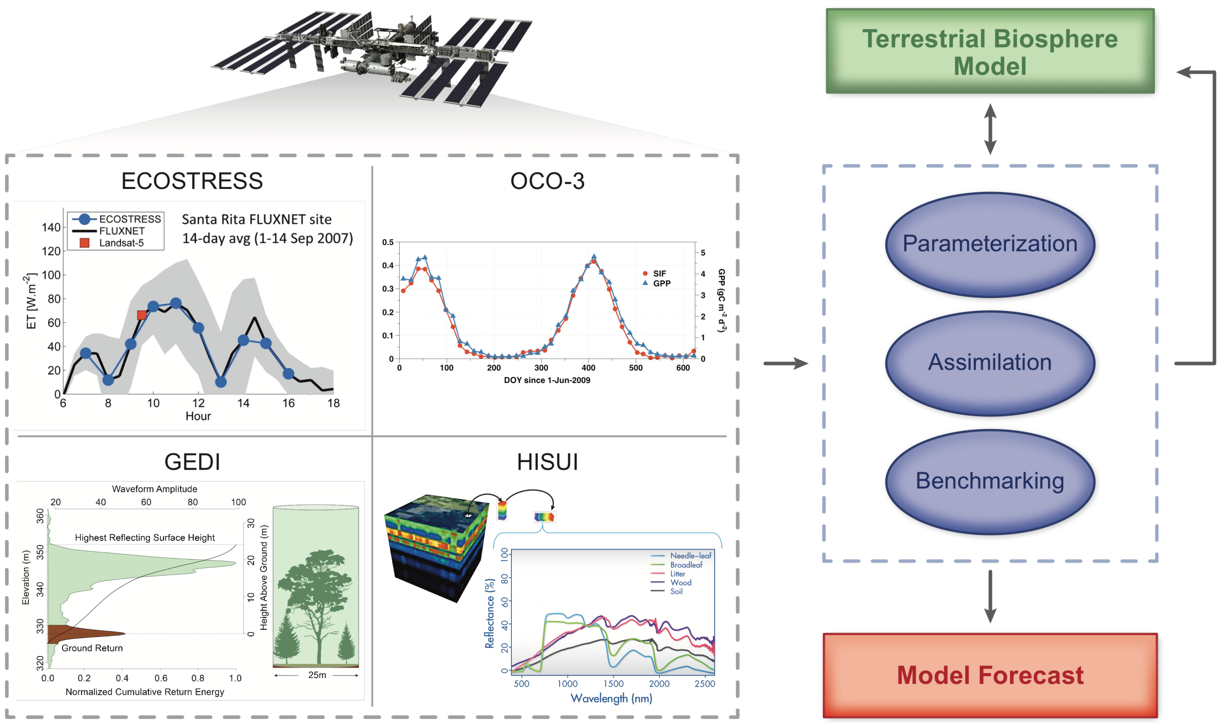

Figure 2. *A conceptual framework for how different data that can be observed from each instrument can be integrated into terrestrial biosphere models to improve their ability to represent and predict ecosystem processes. For ECOSTRESS we show the 14-day average ET as measured by the Santa Rita Fluxnet site with the annual average value of ET as would be measured by ECOSTRESS for each hour of the day. For OCO-3, we show GOME SIF data compared to the MPI-BGC GPP product. For GEDI we show airborne LIDAR (LVIS) waveform from La Selva Biological research station in Costa Rica. For HISUI we show an imaging spectroscopy/hyperspectral image cube and different spectra for different spectral classes. Note that these figures are conceptual to demonstrate the how each dataset can be used.*

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